Regional Studies in Marine Science 31 (2019) 100729

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

The Great Barrier Reef: Vulnerabilities and solutions in the face of ocean acidification

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ARTICLE INFO

Article history:
Received 21 December 2018
Received in revised form 10 June 2019
Accepted 13 June 2019
Available online 10 July 2019

ABSTRACT

As living carbonate-based structures, coral reefs are highly vulnerable to ocean acidification. The Great Barrier Reef (GBR) is the largest continuous coral reef system in the world. Its economic, social, and icon assets are valued at AU$56 billion (Deloitte Access Economics, 2017), owing to its vast biodiversity and services related to commercial and recreational fisheries, shoreline protection, and reef-related tourism and recreation. Ocean acidification poses a significant risk to these ecological and socioeconomic services, threatening not only the structural foundation of the GBR but the livelihoods of reef-dependent sectors of society. To assess the vulnerabilities of the GBR to ocean acidification, we review the characteristics of the GBR and the current valuation and factors affecting potential losses across three major areas of socioeconomic concern: fisheries, shoreline protection, and reef-related tourism and recreation. We then discuss potential solutions, both conventional and unconventional, for mitigating ocean acidification impacts on the GBR and propose a suite of actions that would help assess and increase the region's preparedness for the effects of ocean acidification.

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https://doi.org/10.1016/j.rsma.2019.100729

1. Introduction

The Great Barrier Reef (GBR) is the largest living structure in the world, covering an area of more than 344,000 km^2. Long and relatively narrow, the GBR extends 2300 km alongside Australia's northeast coast with its width ranging between 100 km in the north to 200 km in the south (Brodie and Pearson, 2016). The reef begins in the north at Australia's Cape York Peninsula and ends midway down the eastern coast at Lady Elliot Island, located just 90 km northeast of Bundaberg. 1,115,000 people live within the reef's catchment area that is made up of 35 river basins and, together with the GBR, totals 424,000 km^2 in area (Stoeckl et al., 2011).

The GBR is the most famous and intensively managed marine park in the world. In 1975, the region gained protection through the creation of the Great Barrier Reef Marine Park (GBRMP) with a slightly larger area of 348,000 km^2 designated as a World Heritage Area (GBRWHA) in 1981, signifying the GBR's status as a place of global importance (Hoegh-Guldberg and Hoegh-Guldberg, 2004). Roughly 600 species of coral live on coral dominated reefs. These reefs, however, make up only about 7 percent of the GBRMP by area. Seagrass, mangroves, estuaries and other marine habitats help to host 100 species of jellyfish, 3000 varieties of molluscs, 500 species of worms, 1625 types of fish, 133 varieties of sharks and rays, more than 30 species of whales and dolphins, and various turtles and crocodiles (Great Barrier Marine Park Authority, 2015).

Around the world, coral reefs are already under severe pressure from a number of stressors, including overfishing, pollution, and increasingly frequent and damaging bleaching events. Adding to this suite of threats, they are also among the most vulnerable ecosystems to ocean acidification (OA) because their very framework is dependent on calcium carbonate secreting organisms. Tropical coral reefs are identified as one of the most sensitive ecosystems in the Special Report on Global Warming of 1.5 °C of the Intergovernmental Panel on Climate Change, with mass coral bleaching and mortality projected to increase due to interactions between rising ocean temperature, OA and increased frequency of storms (Hoegh-Guldberg et al., 2018). The report presents an extremely bleak outlook for these ecosystems, with a very high risk of loss of most (70%–90%) coral-dominated ecosystems and remaining structures being weakened due to OA if warming exceeds 1.5 °C. The northern Great Barrier Reef already lost 50% of its shallow water corals during severe bleaching events in 2016–2017 (Hughes et al., 2017).

Coral reefs are biodiversity hotspots and provide habitat to a myriad of organisms, including many fish species. Loss of coral cover, whether due to OA, warming or other pressures on the reef, will lead to a shift in fish communities from species that prefer coral habitats toward species which are successful outside reef settings (Pratchett et al., 2008), with associated potential changes to important reef fisheries. Coral reefs also provide coastal protection from storms and support livelihoods and economic activities such as reef-associated tourism and recreation.

A recent valuation exercise strived to include the social and icon brand value of the Great Barrier Reef and found the total value of the reef to be AU$56 billion, owing to its vast biodiversity and assets related to commercial and recreational fisheries, shoreline protection, and reef-related tourism and recreation (Deloitte Access Economics, 2017). This includes the support of 64,000 jobs in Australia. More recently, a social science approach was undertaken to identify the non-material value of the Great Barrier Reef to people (Marshall et al., 2018). This approach assessed the importance of the GBR for providing lifestyle, sense of place, pride, identity, well-being, and aesthetic, scientific, and biodiversity values according to 8300 people across multiple cultural groups. People across all groups related strongly to all of the cultural values, highlighting the importance of non-material benefits that people derive from iconic ecosystems such as the GBR to people. Yet, these studies tend to oversimplify the value of the GBR and often fail to account for the ways in which a loss of coral reef resources in the GBR will affect the local and regional economies of Queensland or the rest of the world (Hoegh-Guldberg et al. (2019) this issue).

Below, we provide a brief summary of potential impacts of OA on the GBR, followed by a review of the current literature on the economic valuation of the GBR and then discuss factors affecting potential loss of ecosystem services due to OA and other stressors affecting the reef. We focus on three major areas of socioeconomic concern: fisheries, shoreline protection, and reef-related tourism and recreation. We then focus our discussion on protective actions that can address risks from OA and climate change that have already been put into practice in the GBR Marine Park, and discuss scope for future action. We conclude that it will likely be necessary to consider an array of potential measures, and we argue that urgent and substantial cuts in CO_2 emissions must be at the center of any future action, given that climate change and OA are the most serious threats facing the GBR today.

2. Impacts of ocean acidification on the Great Barrier Reef

Ocean acidification refers to the shifts in seawater chemistry that occur as a result of uptake of atmospheric carbon dioxide by the upper layers (300 m) of the ocean. When OA emerged as a dedicated research field in the late 1990s, corals and coral reefs were rapidly identified as potentially vulnerable given their role and sensitivity as key marine calcifiers, and several of the earliest studies on OA focused on corals and coral reefs (e.g. Gattuso et al., 1998; Kleypas et al., 1999). About 15% (579 papers out of 3648) of all papers published to date investigating a biological response to OA have looked at impacts on corals, which represents the third main taxonomic group studied after mollusks (674 papers) and phytoplankton (632 studies) (Ocean acidification bibliographic database on Mendeley, 0000). The body of research on OA impacts on corals include both laboratory and field studies, and many have been carried out in the real-world context of simultaneous warming and acidification. Although results are variable, the overall picture emerging from the research effort to date is that corals and coral reef systems are among the most vulnerable organisms and ecosystems to OA (Hoegh-Guldberg et al., 2007; Anthony, 2016; Kroeker et al., 2010, 2013; IPCC, 2014; Hoegh-Guldberg et al., 2018; IPCC, 2018). This is in large part owing to the reliance of coral reefs on the capacity of corals and other calcifiers to produce calcium carbonate through the process of calcification, and existing calcareous structures' resistance to the process of dissolution, both of which are subject to negative impacts from changing carbonate chemistry conditions associated with OA (Andersson et al., 2011; IPCC, 2014). In addition to calcification, other potential processes susceptible to OA include reproduction, respiration, and photosynthesis, in both corals and other reef organisms such as algae and fish (Andersson et al., 2011; IPCC, 2014).

Several studies have looked specifically at GBR species and communities. A broad review of the implications of climate change, including OA, was compiled as part of the comprehensive climate vulnerability assessment for the GBR (Johnson and Marshall, 2007). This, in combination with more detailed studies published since, have shown a broad array of possible impacts on corals and coralline algae under future OA and warming, e.g. decreased calcification, primary production, settlement, reproduction, and survivorship, increased skeletal dissolution, and changes to gene expression, especially in early life stages (e.g. Anthony et al., 2008; Diaz-Pulido et al., 2012; Doropoulos et al., 2012; Doropoulos and Diaz-Pulido, 2013; Kaniewska et al., 2012, 2015; Moya et al., 2012; Albright et al., 2013; Vogel et al., 2015). Webster et al., 2013 found evidence for altered microbial communities in biofilms of a GBR crustose coralline algae, affecting its ability to perform its role as a substrate for coral settlement. OA and warming have been shown to accelerate bioerosion of corals by microbial communities (Dove et al., 2013), endolithic algae (Reyes-Nivia et al., 2013) and excavating sponges (Fang et al., 2013), adding to the corrosive effects of OA, although these organisms may themselves be susceptible to OA and warming which may limit the negative impacts they will cause in the future ocean (Achlatis et al., 2017; Fang et al., 2018). Several studies have been carried out on GBR fish, with results indicating a change in behavioral and sensory function such as attraction to predator scent, including in commercially important species such as the coral trout (Chivers et al., 2014; Munday et al., 2013), although similar changes were not found in other coral reef fish species (Sundin et al., 2017). Other examples of limited or positive impacts of OA on the GBR have been found, e.g. several GBR seagrass species seem to increase net photosynthesis rates under OA (Ow et al., 2015) and biotic processes (e.g. photosynthesis) in reef sediments seem unaffected by OA (Fink et al., 2017). It is not yet fully understood if OA increases corals' susceptibility to bleaching (Anthony et al., 2008) even though it seems increasingly unlikely (Albright, 2018).

OA has the potential to affect not only biological processes but also ecological interactions between species, with some species benefitting to the detriment of others. For example, seaweed may become increasingly competitive compared with corals under future OA conditions on the GBR (Diaz-Pulido et al., 2011). Coral and coralline algae communities present in naturally acidified waters around CO_2 seeps in Papua New Guinea are less diversified and complex as compared to similar communities outside the seep site (Fabricius et al., 2011, 2015). Less diverse and less structural complexity translate to less appropriate habitat for fish and other reef organisms with potential impacts on fisheries and other ecosystem services. Such studies provide 'windows into the future' and can, together with other methods, provide some much-needed insight into responses at the ecosystem level, necessary to understand any changes to services provided by those ecosystems.

It is likely that GBR communities already calcify less due to OA. Calcification rates increased by 25% in small patch reefs in mesocosm experiments when carbonate chemistry was restored to preindustrial compared to present-day conditions (Dove et al., 2013) and Albright et al. (2016a) found that net community calcification increased when water with conditions corresponding to preindustrial levels were applied to a GBR reef flat in a controlled field perturbation experiment. Decreased calcification is supported by results from skeletal records of massive corals from the inshore Great Barrier Reef, which indicate an 11% decline in calcification between 1990 and 2005, the fastest and most severe decline in at least 400 years (De'ath et al., 2009). Another study argues that decreased community calcification on the Lizard Island reef flat over the last three decades might be primarily due to OA (Silverman et al., 2014).

According to a review of regional accretion rates by Kennedy et al. (2013), the Great Barrier Reef has much lower net accretion rates when compared to areas such as the Coral Triangle, suggesting that the GBR may have a relatively higher sensitivity to OA in comparison to other reef systems. Dove et al. (2013) showed that reefs may transition from net calcium carbonate accretion to net dissolution by the end of this century, which has also been confirmed in other areas of the world (Silverman et al., 2009; Perry et al., 2013), at CO_2 seep sites (Enochs et al., 2016), by CO_2 enrichment experiments in the field (Albright, 2018) and by model projections (Hoegh-Guldberg et al., 2007).

Like in other reef systems, carbonate chemistry is highly variable on the GBR, both in time and space, and driven by both physical (e.g. temperature, mixing with water masses from adjacent waters) and biological (photosynthesis, respiration) processes (Albright et al., 2013; Anthony et al., 2013; Kline et al., 2012; Uthicke et al., 2014). Corals are likely to experience changes in pH which go beyond declines projected for the end of the century on a regular basis. It is unknown though if this high natural variability confers enhanced resistance to OA (Albright et al., 2016b). Many laboratory experiments to date have used scenarios of open ocean carbonate chemistry conditions rather than more locally relevant conditions. Cornwall et al. (2018) found limited response and some evidence for faster calcification under extreme OA in corals and coralline algae from a site with high daily pH variability in North West Australia compared to a low-variability site. There seems to be little evidence for acclimation and adaptation to OA in the GBR (but see Moya et al., 2015).

In summary, results from laboratory, field and model studies converge to show that we can expect OA, particularly in combination with warming, to cause major changes in GBR communities, including loss of reef framework, biodiversity and ecosystem services. While warming remains the most acute concern for the GBR, with mass bleaching events expected to continue in the years to come (Hughes et al., 2018), OA adds to the stress from warming and makes reefs less resilient, slowing recovery after bleaching events.

3. Potential socio-economic impacts of Great Barrier Reef loss

While the evidence for adverse effects of OA and climate change on corals and coral reef ecosystems grows, and our capacity to project future changes improves, the challenge remains to project what these effects will mean for human communities depending on the reefs. The estimation of future losses in economic and societal value of coral reefs is complicated by the uncertainty associated with projections of human behavior in response to degradation of coral reefs, since human behavioral responses are notoriously difficult to predict with confidence given available data and knowledge of system dynamics (Pendleton et al., 2016a,b; Pendleton and Edwards, 2017).

Hoegh-Guldberg et al. (2019) review existing literature on the potential economic consequences of losses to coral reef fisheries, coastal protection and tourism, and discuss factors affecting these losses (this issue). For instance, the authors point out that people may simply continue to take advantage of the decreased services provided by the reefs, albeit with less profit, enjoyment etc., or shift to using substitutes for lost services (e.g. recreation activities which are not dependent on the reef). These same reef users could also turn to other ecosystems that could provide similar services (e.g. mangroves in the case of shoreline protection and tourism), adapt their activities, or move. Regions like the GBR where most people do not rely on the reef as primary source of food, and where there are more options to adapt, would tend to be less vulnerable and more resilient to change.

Below we outline some of the key issues that affect the potential loss of value if coral reef ecosystems decline in the GBR. It is hoped that this analysis will spark a more nuanced discussion about the value of coral reef ecosystem services, not to lessen in any way the importance of these systems, but to encourage research on the human dimensions of loss of ecosystem services to better understand and be able to suggest more appropriate solutions to reduce impacts of coral reef loss. A full presentation of this approach and discussion about the methods used, including assumptions and limitations, is presented in Hoegh-Guldberg et al. (2019) (this special issue).

4. Great Barrier Reef fisheries

4.1. Current value

The estimated economic contribution from the GBR fisheries cannot be wholly ascribed to the coral reef within the marine park because much of the park is habitat for non-reef species such as pelagic fish. Valuations that have examined the economic contribution of commercial and/or recreational fisheries within the GBR, with the exception of Teh et al. (2013), have not distinguished between reef-dependent and non-reef dependent fisheries. Nevertheless, the range of estimates of the economic contribution from GBR fisheries provides insight into the value of reef ecosystems as a component of GBR fish habitats.

Many studies or reports that examined GBR fisheries estimated the gross "value" of the GBR's commercial fisheries – a measure of revenues. Gross revenues can be useful in determining the societal importance of an ecosystem service, but are an overestimate of the "value" of the good or service because the costs of production inputs, including environmental degradation or depletion of natural resource stocks, are not accounted for. The estimates for the annual gross revenue from GBR commercial fisheries ranged between AU$119 million (does not include aquaculture) (1999–00) and US$199 million (includes aquaculture) (2015–16) (Deloitte Access Economics, 2017; Driml, 1999; KPMG Consulting, 2000; Oxford Economics, 2009; Productivity Commission, 2003) to US$407 million for reef-dependent fisheries (derived from Teh et al., 2013; see also Pendleton et al., 2016a,b).

Gross value added ("GVA") focuses more on the additional value created by coral reef fisheries and is comprised of wages earned, profits and production taxes (less subsidies) that result from GBR fishing activity (Deloitte Access Economics, 2017). Beginning in 2005, Access Economics ("Deloitte Access Economics" as of 2011) generated a series of reports for the GBRMPA that examined the "economic contribution" of the Great Barrier Reef in terms of "value added" or, in other words, the value of gross output (total revenue) minus the intermediate costs of producing the goods and services (Deloitte Access Economics, 2017). Deloitte Access Economics (2017) found that the annual value added from commercial fishing and aquaculture in and around the Great Barrier Reef was AU$162 million for Australia (2015–16) of which AU$116 million was considered "direct value" or the economic contribution resulting from consumer transactions within the commercial fishing sector. About AU$95 million of the total revenues (AU$199 million) came from line, net, pot and trawl fishing, but the contribution of coral reefs to these economic contributions was not calculated.

Gross Operating Surplus ("GOS") is a measure of net value and is, in simple terms, the GVA minus employee compensation, minus taxes on production and plus subsidies received (Australia Bureau of Statistics, 2000). Oxford Economics (2009) used a GOS estimate from GBR commercial fishery activity as a proxy measurement for "producer surplus", or the amount that a producer receives above the amount that the producer is willing to accept – a measure of net value (Oxford Economics, 2009). Applying a GOS/GVA ratio of .62 (from 2004 Queensland Regional Input–Output Tables) to an earlier 2006–07 Access Economics (Access Economics Pty Ltd, 2009) GVA estimate of AU$65.7 million per year (adjusted to 2009 AU$), the study found an estimated annual GOS of AU$41 million (2009) from the GBRMP-dependent commercial fisheries (which includes non-reef dependent fisheries).

Recreational fishing on the Great Barrier Reef is of the same order of magnitude of economic importance as commercial fishing. Annual gross revenue estimates for recreational fishing ranged from AU$108 million (1997–98) to AU$240 million (1999–00) (Driml, 1999; KPMG Consulting, 2000; Productivity Commission, 2003). Deloitte Access Economics (2017) estimated the total annual "recreational" expenditures to be AU$415 million, mostly made up of "equipment" at AU$241 million, followed by "fishing" at AU$70 million, and also "boating", "sailing" and "visiting an island". The annual value added from "recreation" was AU$346 million for Australia, of which AU$206 was direct value added (2015–16). Oxford Economics (2009), using the same method employed for commercial fisheries, estimated the annual GOS ("producer surplus") associated with GBR recreational fisheries to be AU$8.6 million (Access Economics Pty Ltd, 2009; Oxford Economics, 2009).

Consumers, in this case the recreational fishers, also enjoy benefits from coral reefs that are beyond what they spend to access reef areas, and over the years, economic valuation methods, such as the travel cost method and contingent valuation have been used to estimate the "consumer surplus". Oxford Economics (2009) found the estimated annual consumer surplus for GBRMP recreational fisheries to be AU$70.1 million (2009) (the average of two transferred values from previous studies that were derived from survey work and the travel cost method (Blamey and Hundloe, 1993; Prayaga et al., 2010).

4.2. Factors affecting potential losses associated with GBR fisheries

The annual net economic value from commercial fishery associated with the Great Barrier Reef is likely to be on the order of just over AU$40 million/year (Oxford Economics, 2009). This represents the maximum amount of economic net value from fishing that would be lost if fishers simply stop fishing and inputs and costs were saved and inputs used elsewhere. Recreational fishing generated just under AU$9 million/year in net value to producers, and recreational fishers were estimated to enjoy approximately AU$70 million annually in net benefits (Oxford Economics, 2009). The proportion of these benefits that depend on coral reefs is unclear. If recreational fishers turn to other activities on the water, expenditures associated with recreational fishing may not change much (expenditures on boating, sailing, and equipment make up more than 80% of recreation related expenditures associated with access to the GBR.) With business-as-usual as the measure of impact of coral reef loss, these estimates are likely to be overestimates of the true net economic cost of coral reef loss to fishing.

5. Shoreline protection provided by the Great Barrier Reef

5.1. Current value

The GBR's patchy series of 2900 coral reefs, made up of both barrier and fringing (about 760 of the total) (Oxford Economics, 2009), provide coastal protection from storms, waves and erosion to more than 316,000 coastal residents (Pendleton et al., 2016a,b; Burke et al., 2011). We found only two studies that provided estimated values for the coastal protection provided by the GBR. Cesar et al. (2003) estimated a shoreline protection value of US$629 million (currency year not provided) per year for all of Australia's 49,000 km^2 of coral reef, and it appears that this value was based on "transferred" 2001 property values from a Hawaii coral reef valuation.[1] Scaled to the GBRMP area and adjusted for inflation and exchange rates, this figure translates to a value of GBRMP coastal protection of about AU$438 million per year (2009 AU$) (Cesar et al., 2002, 2003; Oxford Economics, 2009).

Oxford Economics (2009) used the replacement cost method to estimate coastal protection provided by the GBRMP. By taking the cost to construct erosion preventative revetment walls ($2300 per meter) in South Mission beach, Australia (about 15 km south of Cairns City) (Queensland Environmental Protection Agency, 2005) and applying this cost to the GBRMP reef length (2300 km), the study estimated a capital cost of AU$5.3 billion (2009 AU$) for GBRMP coastal protection. Note, that replacement cost estimates are often discouraged because unless replacement is or would be undertaken, there is no way of knowing whether replacement costs are significantly higher than actual value people place on the lost service (Barbier, 2015). Since land along the GBR coast is used in a variety of ways and has varying vulnerabilities to storms, waves, and erosion, it is problematic to use a single replacement cost for one area of GBRMP in order to estimate the value of coastal protection for the whole coastline. There is a clear need for more data collection and better estimates of the value of shoreline protection here (see Figs. 1 and 2).

5.2. Factors affecting potential losses

Already, coastal areas within the Great Barrier Reef Catchment Area are subject to erosion. Only a small proportion of the coast protected by the Great Barrier Reef is developed (see Fig. 3) for residential uses; much is considered outer-regional, remote, or very remote. The areas most affected by recent coral reef death also are the areas of lowest population density. The coastline in some developed and urban areas, especially in urban areas of northern Cairns, have already been hardened. Furthermore, many areas in the region already are classified as "erosion prone" and steps have been taken to address erosion and lost shoreline protection. It is unlikely that hard armoring of the shoreline, like that envisioned by Oxford Economics (2009) will be undertaken for the entire stretch of coast at risk. Mangroves may also provide important shoreline protection in many of the areas most affected by a loss of coral protection. Other options include adapting coastal structures to periodic flooding and managed retreat, for instance in conservation and agricultural areas.

[1] Cesar et al. (2002), the cited Hawaii coral reef valuation, did not provide a specific estimate for "coastal protection", although it did include the coastal protection services provided by coral reefs as contributing to the "annual reef-related property value in Hawaii in 2001".

6. Reef-related tourism and recreation attributable to the GBR

6.1. Current value

Several studies have tried to assess the economic contribution of coral reefs to tourism. As with the economic contribution of GBR fisheries, not all tourism to the GBR region can be attributed to coral reefs. Some tourists may come simply to enjoy beach or water features that would occur regardless of coral reef existence. Studies and reports have indeed attempted to isolate estimates of reef-related tourist expenditures from the broader category of GBR tourism expenditures. Annual reef-related expenditure estimates range from AU$480 million (2012) to over US$2 billion (2013) (Deloitte Access Economics, 2013; Oxford Economics, 2009; Spalding et al., 2017); and estimates of net benefits (consumer surplus) to tourists have ranged from AU$474 million (2009) (Oxford Economics, 2009 adjusted to reflect only visitors who were motivated by coral site visitation) to as much as US$1.6 billion annually (2000) (Carr and Mendelsohn, 2003; Deloitte Access Economics, 2017 not adjusted to reflect reef-motivated tourism). Oxford Economics (2009) estimated the annual GOS (producer surplus) associated with all GBR coral site visitors to be AU$202 million (2009 AU$).

To better understand the importance of coral reefs in supporting coral tourism, Spalding et al. (2017) attempted to map and find the "reef-coast" tourism economic contribution for all countries (worldwide) and territories with greater than 50 km^2 of reef that had total reef-related expenditures greater than $10 million per year. The estimated expenditures of "reef-coast" tourism and recreation (not including fishing) for all of Australia (mostly attributed to the GBR) were just over US$2 billion per year or a mean value of US$51,883 per km^2 of coral reef (2013 US$). The authors divided the total economic contribution of reef-coast tourism into "reef-adjacent"[2] tourism expenditures of US$473 million per year and "on-reef"[3] expenditures of US$1.7 billion per year (2013 US$). The study estimated that an annual 1.45 million trip equivalents were taken for GBR "on-reef" tourism. This number is similar to the industry estimates of 1.1 million people visiting coral sites and 1.8 million visits to the GBRMP in 2013 (Spalding et al., 2017). The location and intensity of "on-reef" tourism mapped in Spalding et al. (2017) also corresponded to the GBR Marine Park Authority finding that over 80 percent of tourism to the GBRMP took place in only 7 percent of the region (near Cairns and Whitsunday) (Great Barrier Reef Marine Park Authority, 2014; Spalding et al., 2017).

Deloitte (Deloitte Access Economics, 2013) used data from tourism operator logbooks that were submitted as part of the Environmental Management Charge returns in order to estimate "reef-related" tourism expenditures for the Great Barrier Reef Catchment Area (GBRCA). Based on the GBRMP's estimate of 1.92 million visitor days spent on the reef (2012) and average daily expenditure estimates, Deloitte Access Economics (2013) found the annual tourism expenditures specific to the reef to be approximately AU$481 million with a (smaller) value added of AU$389 million (2012). Deloitte Access Economics (2013) also estimated that GBRCA reef-related tourism supported the equivalent of approximately 4831 full-time jobs (2012).[4] Clearly, the

[2] Reef-adjacent values include indirect benefits from coral reefs, including provision of sandy beaches, sheltered water, food, and attractive views and values (visitor numbers and expenditures) were set as a proportion of 10% of all coastal non-urban tourism values within 30 km of a coral reef.

[3] "On-reef values were based on the relative abundance of dive-shops and underwater photos in different countries and territories". (Spalding et al., 2017, p. 104).

[4] (Deloitte Access Economics, 2013) also estimated expenditure values for all GBR tourism (regardless of whether reef-related). These estimates were later

Fig. 1. The Great Barrier Reef Marine Park, Queensland Australia.

large difference in reef-associated expenditure estimates from Spalding et al. (2017) ($2.2 billion in 2013 US$) and Deloitte Access Economics (2013) ($481 million in 2012 AU$) demonstrates that the methodology for determining the economic contribution of coral reefs is still developing.

updated in (Deloitte Access Economics, 2017): annual expenditures came to AU$7.8 billion (2015–16); total value added was AU$5.7 billion (AU$2.7 billion direct value added); and total employment (FTE) was 58,980 FTE (35,485 FTE direct employment).

Oxford Economics (2009) estimated the annual GOS (as proxy for producer surplus – an estimate of net value), or industry benefits, derived from tourism to GBR coral sites. A GOS/expenditure ratio of .15[5] was applied to annual tourist expenditures[6] of

[5] Ratio from Australian Bureau of Statistics (ABS) (2008b) *Tourism Satellite Account 2006-07*, ABS Cat. No. 5249.0

[6] Based on figures from *Bureau of Tourism Research (2003) Assessment of tourism activity in the Great Barrier Reef Marine Park Region.*

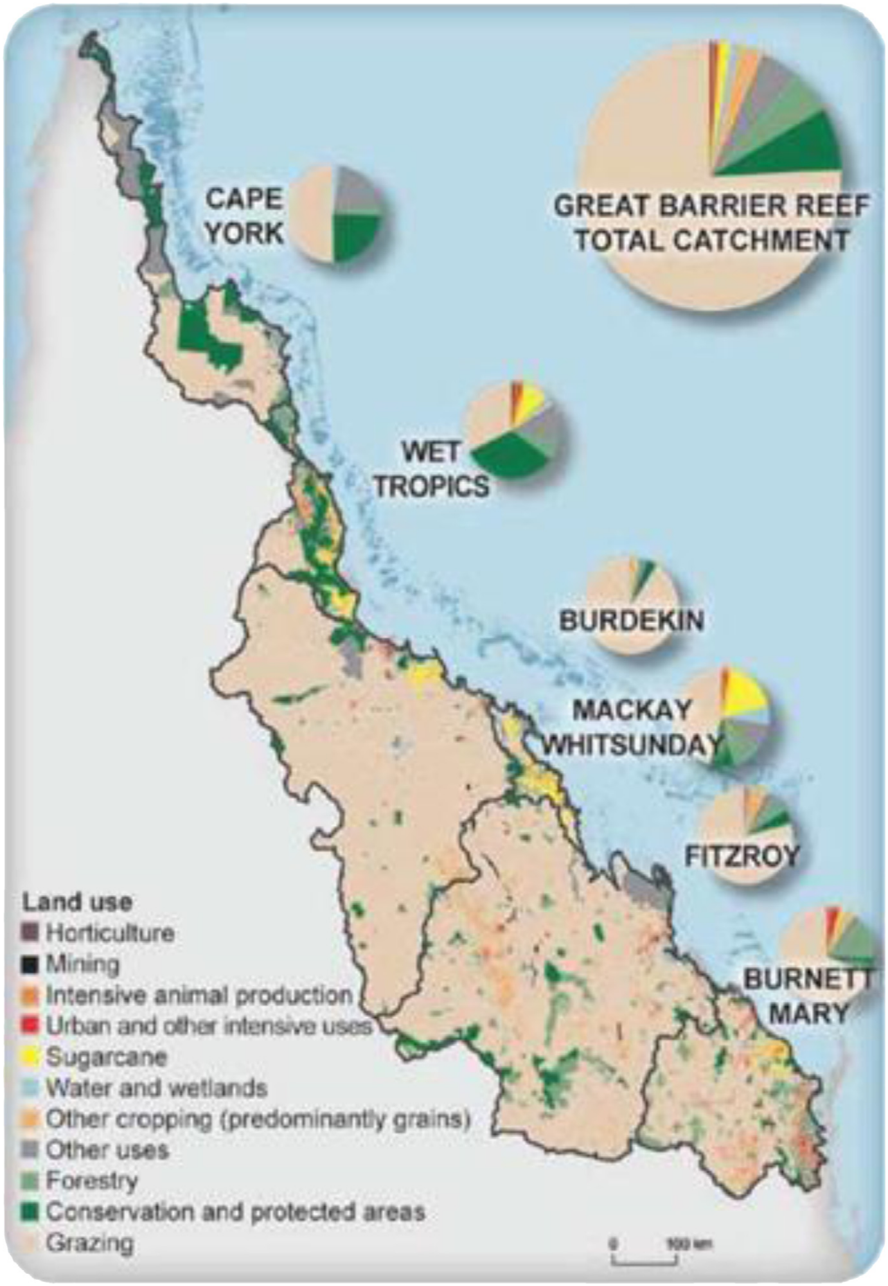

Fig. 2. Landuse with the Great Barrier Reef Marine Park.
Source: http://www.reefplan.qld.gov.au/about/regions/great-barrier-reef/assets/land-use-map.jpg.

AU$1.3 billion (2009 AU$) for the GBR coral sites. The annual GOS for coral site tourism as a whole was an estimated AU$202 million (2009 AU$) for the GBR, but this figure only reflects industry benefits from tourists who happened to visit the GBR coral sites and were not necessarily motivated to travel to the GBR because of coral reef presence. Taking this distinction into consideration, the study assumed that 50 percent of overnight visitors were motivated to make trips based on the presence of the GBR and all of the day-trippers were motivated by the reef's existence, resulting in an adjusted GOS estimate of $102 million per year (2009 AU$).

Deloitte Access Economics (2017), using the travel cost method, found that the estimated annual consumer surplus for domestic tourists visiting the GBR was AU$1.5 billion (2017); and, by use of benefit transfer and adjustment of a previously estimated recreational consumer surplus value (Rolfe and Gregg, 2012), estimated an annual recreational consumer surplus of AU$170 million (2017 AU$) for recreational visitors (i.e. day visitors) to the GBR.[7] Fourteen years prior to (Deloitte Access Economics, 2017), Carr and Mendelsohn (2003) had been the only study to examine the consumer surplus associated both with domestic and international tourism to the GBR, and found a value range of US$710 million to US$1.6 billion per year (of which $400 million accrued to domestic visitors) (2000 US$).

Oxford Economics (2009) was the only study that adjusted its GBR consumer surplus estimate to only include visitors who

[7] Rolfe and Gregg (2012) measured the consumer surplus attributed to beach recreational values (as opposed to recreation specific to coral reef), although some of beach recreation may be attributable to coral reefs (e.g. "observing nature" or "water sports" see Rolfe and Gregg (2012)).

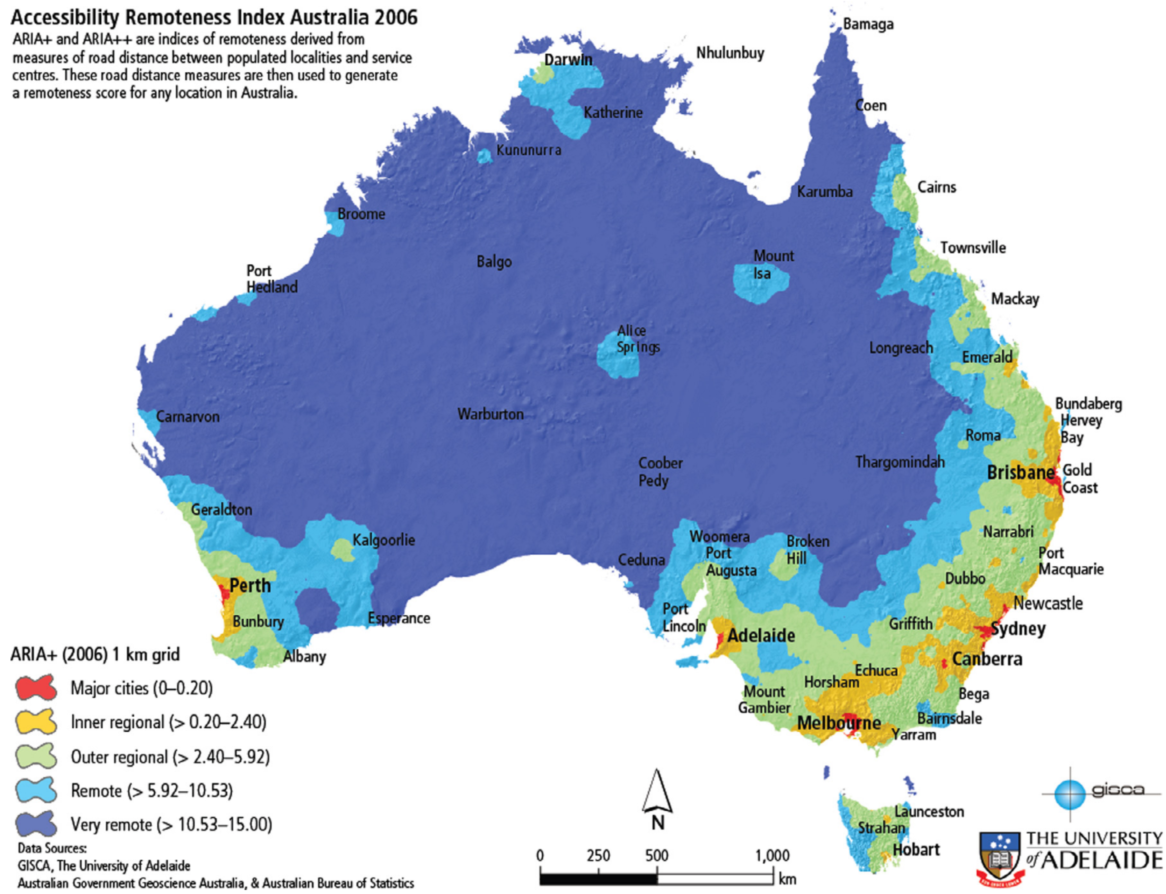

Fig. 3. Accessibility remoteness Index for Australia.
Source: https://aifs.gov.au/publications/families-regional-rural-and-remote-australia/figure1.

visited GBR coral sites and were motivated to come to the GBR by coral site visitation. Identical to the producer surplus estimate above, the study assumed 50% of overnight (domestic and international) GBR visitors and 100% of day trippers were motivated by the presence of coral sites. The study found, after adjusting for "reef-motivated" visitors, the estimated annual consumer surplus was AU$474 million (2009).[8]

6.2. Factors affecting potential losses attributable to GBR tourism

Reef-related tourism infrastructure and capital could be redeployed to other tourism activities. While losses to the tourism industry are likely to be large in the short-term, overall we would expect the economy to shift to other types of sun, sea, and outdoor recreation. Tourists who already planned to go to the GBR or had that on their 'bucket list' would likely lose a considerable amount of their consumer surplus, in the short term. Over time, international tourists would choose to visit other destinations (including those within Australia). The long- term impact to international tourism wellbeing (net value) would likely be small. As is always the case, those who face lower travel costs stand to lose a higher proportion of their consumer surplus (wellbeing) if the next best option requires substantially higher travel costs. Domestic tourists (who currently enjoy benefits of AU$1.5 billion) who continue to visit coral reefs may have to travel south or leave Australia entirely. Day use visitors stand to lose an even larger proportion of their current value (AU$170 million/year), although these visitors may simply take up other recreational activities.

The above discussion demonstrates the inherent complexity of trying to put an economic value on ecosystem services provided by the GBR. Even when discussing more realistic estimates, potential costs of lost services remain very high – and would justify investment in their protection. Also, these discussions do not include societal and iconic value as discussed in Marshall et al. (2018), which is even more difficult to assess. Clearly, the value of the GBR is difficult to estimate, and the potential loss of value of reef loss is even more so. While many people feel the GBR is priceless, both to Australians and indeed people around the world, the costs of avoiding loss are very real (Deloitte Access Economics, 2017).

7. Solutions

7.1. Current actions and commitments to protect the Great Barrier Reef from OA and climate change

The Great Barrier Reef Marine Park (GBRMP), which encompasses most of the Great Barrier Reef region, was created in 1975 in response to increasing concerns about threats to the reef, in particular plans for mining the reef for mineral and gas.

[8] The Oxford Economics (2009) per person per visit consumer surplus for the GBR coral site visitors before adjusting for tourists who were specifically motivated by coral sites, was AUS$892 - AUS$1202 (2009). This estimate was similar to the Carr and Mendelsohn (2003) figure of AUS$600 (domestic) – AUS$1500 (international) (2009 AUS$) (adjusted by Oxford Economics (2009) from US$350 - US$800 (2000 US$)). These values were also similar to the average consumer surplus per person per domestic trip estimate of AUS$662 (2017) in (Deloitte Access Economics, 2017).

The GBRMP Act of 1975 established a large number of protective actions, including the complete prohibition of mining and drilling activities on the reef. In 1981, the GBR became a UNESCO World Heritage Area, with world heritage values protected under Australian environmental law.

The GBRMP is jointly managed by the Great Barrier Reef Marine Park Authority, the state of Queensland and the federal Government (Department of Environment and Energy). Current management is based on the GBRMP Act of 1975 and the ambitious Reef 2050 Long Term Sustainability Plan (the 'Reef 2050 Plan' for short) launched by Commonwealth and Queensland governments in 2015 in response to recommendations from the UNESCO World Heritage Committee in 2013. The Committee acknowledged the significant efforts undertaken by the Australian and Queensland governments in developing the Reef 2050 Plan, as shown by the decision not to inscribe the Great Barrier Reef as in-danger in 2015.

The Reef 2050 Plan was developed with input from a broad range of stakeholders including scientists, communities, traditional owners, industry and non-government organizations. It addresses the concerns of the World Heritage Committee through a series of actions, targets, objectives and outcomes across seven key themes - including biodiversity, water quality and ecosystem health. Commonwealth and Queensland government investment in reef management, research and protection is projected to be more than AU$2 billion dollars over the next decade (Reef 2050 Plan). It is the most comprehensive strategy to date for addressing the key issues facing the Reef, with stringent plans for reviewing progress and updated actions and priorities. Each review cycle will be informed by improved scientific understanding, including the comprehensive GBRMP Outlook reports, published every 5 years to evaluate the success of the GBRMP and the health status of the reef. The most recent edition came out in 2014 and placed climate change and OA among the top risks to the reef, together with land-based runoff and coastal development (Great Barrier Reef Marine Park Authority, 2014).

Although mitigating local stressors does not directly address the threats of climate change and OA, there is increasing focus on reducing local stress factors to increase the resilience of reefs to global stressors associated with climate change (Hock et al., 2016; Roberts et al., 2017). Measures in the Plan relevant to building resilience to OA include regulations to ensure fishing is ecologically sustainable. Avoiding overfishing of herbivores is an important means to help prevent proliferation of algae at the expense of corals (Diaz-Pulido et al., 2011). Comprehensive tourism permitting arrangements help ensure that negative impacts from tourist activities are kept to a minimum. The Plan also includes stringent controls on wastewater discharge and programs to reduce land-based sources of pollution (especially from agriculture). The GBR receives run-off from 38 river catchments along its coastline, which drains 424,000 km^2 of coastal and inland Queensland (gbrmpa.gov.au). Reefs within 10 km of the coast (approximately 20% of the total number of GBR reefs) are under direct terrestrial influence from freshwater, sediment, nutrient, and organic carbon runoff (Uthicke et al., 2014). Nitrogen pollution and eutrophication contribute to acidifying coastal waters, exacerbating the effects of OA (Cai et al., 2011; Duarte et al., 2013). The Plan includes ambitious targets to reduce dissolved inorganic nitrogen loads in priority areas by at least 50% by 2018, with the goal to achieve an 80% reduction in nitrogen by 2025 (Reef 2050 Plan). Other concrete water-quality targets include a reduction in pesticide loads by at least 60% in priority areas by 2018, and a permanent ban on the disposal of dredge material in both the Great Barrier Reef Marine Park and the World Heritage Area from capital dredging projects. Efforts to date have already proved to be successful; pesticide load has been reduced by 28%, sediment load by 11%, total nitrogen load by 10%, and dissolved inorganic nitrogen by 16% compared to a 2009 baseline (Reef 2050 Plan).

Despite the identification of climate change and OA as among the major threats to the reef in the Outlook report of 2014, and a dedicated GBRMPA 'Great Barrier Reef Climate Change Action Plan (2012–2017)' which outlines activities that will help adjusting to climate change, the first edition of the Reef 2050 Plan released in 2015 did not include much emphasis on climate change and solutions to mitigate and adapt to its effects. In response to the mass coral bleaching events in 2016 and 2017, the first scheduled mid-term review of the Reef 2050 Plan was brought forward and resulted in an updated report released in July 2018 (Reef 2050 Plan, 2018). The updated version identifies climate change and OA as the most significant threats to the future of coral reefs worldwide, and includes a number of new actions specifically focused on increasing resilience in the face of climate change and OA. These include investigating and supporting local reef restoration activities, supporting research to produce high-resolution climate change projections to inform regional adaptation strategies, supporting land sector carbon reduction projects, and developing a method for using blue carbon as a carbon abatement activity.

Active local restoration is included as a priority strategy in the GBRMPA's 'Blueprint for resilience', published in 2017 (GBRMPA, 2017) although such measures have not yet been widely applied to the GBR. The Blueprint informed the addition of actions on restoration in the updated Reef 2050 Plan from 2018 and signals a change in management of the GBR. The Reef 2050 Plan states that *'Managing coral reef ecosystems, in light of recent bleaching events, cumulative pressures and possible climate change trajectories, requires a different approach. In the past, management has focused on measures designed to protect values (e.g. zoning plans) or mitigate risk (e.g. permits and best practices). In the future, management will adopt additional measures to not only protect and mitigate but also actively support Reef recovery.'* The 2018 edition of the Plan includes new actions on the investigation, improvement and scaling up of reef restoration methods based on the best available science, and to fund research to develop large-scale restoration methods including assessing the feasibility of increasing the thermal tolerance of Great Barrier Reef corals. The kind of restoration techniques that may be envisioned are not mentioned, but any interventions would be regulated through and approved by the GBRMPA (https://www.gbrrestoration.org/home).

The Plan also mentions international and national efforts and plans to mitigate and adapt to climate change, such as the Paris Agreement, the Queensland Climate Transition Strategy, and Australia's support to international efforts on climate action, e.g. through the Green Climate Fund. Australia's climate mitigation commitments include a $A2.55 billion emissions reduction fund to help reach Australia's 2020 emissions target (reducing emissions to 5% below 2000 levels by 2020). Under the Paris Agreement, Australia has committed to reduce emissions by 26%–28% below 2005 levels by 2030. The Plan states that "*international efforts to reduce global climate change, combined with action at national and local levels to build the resilience of the Reef by reducing impacts, is the best insurance for protecting the Reef*".

7.2. Unconventional solutions applicable to the GBR

Less traditional approaches to safeguard the GBR and associated services have also been proposed, including techniques like phytoremediation, chemical remediation, and assisted evolution.

Phytoremediation takes advantage of the fact that seagrasses are carbon limited and will probably benefit from rising seawater CO_2 concentrations. Increased net photosynthesis rates under OA

Table 1
Great Barrier Reef Fisheries: Estimated economic benefits.

Study	Currency Year & Data Year for Commercial Fishing Estimate	GBR Commercial Fishing Economic Contribution	Currency Year & Data Year for Recreational Fishing Estimate	GBR Recreational Fishing Economic Contribution
(Driml 1999) GBRMP Fisheries	Currency:1996 AU$ Data: 1991-92 fishing volume data (selected major commercial species and prawns from Queensland Fisheries Mgmt Authority (QFMA)) Annual gross revenue of $128 million (1991-92) was inflated to the 1996 equivalent	Annual gross revenues: $143 million (1996 AU$)	Currency: 1996 AU$ Data: Direct annual average expenditures of $3700 on recreational fishing and boating (1990) transferred from (Blamey and Hundloe 1993) and inflated to 1996 AU$; no. of boats used in the GBRMP based on Queensland Dept. of Transport (QDT) 1995 records	Annual total direct expenditures: $122 million (1996 AU$)
(KPMG Consulting 2000) GBRMP Fisheries	Currency: AU$ in nominal dollars for each year Data: based on QFMA volume data and price for given year	Annual gross revenues: $121 million (1994-95); $149 million (1995-96); $141 million (1996-97); $136 million (1997-98 AU$) Total Annual Impact (includes indirect output and employment): $194 million (1994-95 AU$) Initial Annual Employment: 1,568 (1994-95) Total Annual Impact on Employment (includes indirect output and employment): 2,720 (1994-95)	Currency: AU$ in nominal dollars for each year Data: Direct annual average expenditures of $3700 on recreational fishing and boating (1990) transferred from (Blamey and Hundloe 1993) and adjusted for inflation. No. of boats for each year based on QDT data	Annual total direct expenditures: $120 million (1994-95); $118 (1995-96); $113 million (1996-97); $108 million (1997-98 AU$) Total Annual Impact (includes indirect output and employment): $255 million (1994-95 AU$) Initial Annual Employment: N/A Total Annual Impact on Employment (includes indirect output and employment): 2,008 (1994-95)
(Productivity Commission 2003) GBRCA Fisheries	Currency: 1999-00 AU$ Data: based on volume of catching fish, including prawns and finfish, from ocean or coastal water (not aquaculture) and estimates of landed prices of catches from Australia Bureau of Agricultural & Resource Economics (ABARE) 2001 Employment data refers to marine fishing from Australia Bureau of Statistics (ABS) 2001	Annual gross revenues: $119 million (1999-00 AU$) Total employed: 641 (August 2001)	Currency: 1999-00 AU$ Data: Annual expenditures by recreational fishers of lagoon and catchment from Queensland Fisheries Service (QFS) unpublished data	Annual total direct expenditures: $240 million (1999-00 AU$)

(*continued on next page*)

were found in several GBR seagrass species (Ow et al., 2015). Manzello et al. (2012) showed that seagrass beds in proximity of coral reefs in the Florida reef tract can modify carbonate chemistry conditions locally, creating favorable conditions for the adjacent corals. Laboratory and modeling studies show that phytoremediation may be a viable option for parts of the GBR (Unsworth et al., 2012; Mongin et al., 2016) even though cost and scalability will be challenging. Mongin et al. (2016) found that for Heron Island in the southern GBR, a kilometer-scale farm could only partially delay the impacts of OA by 7-21 years, depending on future CO_2 emissions trajectories.

Chemical remediation approaches propose to modify carbonate chemistry conditions by adding alkaline material such as silicate rock (olivine) or calcium oxide (lime) or speed up weathering processes of calcium carbonate (limestone) electrochemically. Great care would be needed to ensure that these methods do not generate CO_2 (e.g. lime production). A field experiment conducted on One Tree Island in the southern GBR manipulated carbonate

Table 1 (*continued*).

(Oxford Economics 2009) GBRMP (used interchangeably with the GBRWHA) Fisheries	Currency year: 2009 AU$ Data year: Gross Value Added (GVA) from 2006-07 estimate by (Access Economics Pty Ltd 2009) GVA was adjusted based on wild harvest to total commercial revenue in order to "remove" value from aquaculture Gross Operating Surplus (GOS)/GVA ratio of .62 from Queensland govt. data 2004 Assumes 30% loss of value from bleaching based on (Hoegh-Guldberg and Hoegh- Guldberg 2004)	Annual GVA: $65.7 million for GBRMP (2009 AU$) Annual GOS (PS): $40.7 million for GBRMP (2009 AU$)	Currency: 2009 AU$ Data: 1990 and 2007 - took average CS values from previous studies (Blamey and Hundloe 1993; Prayaga, Rolfe, and Stoeckl 2010) Gross Value GVA from 2006-07 estimate by (Access Economics Pty Ltd 2009) GOS/GVA ratio from Queensland govt. data 2004 No assessment made for costs due to bleaching as this is reliant on whether fishers gain enjoyment from the experience or the catch.	Annual consumer surplus (CS): $70.1 million for GBR; $10.1 million for Cairns (2009 AU$) Gross revenue figure not provided Annual GVA: $42 million for GBRMP (2009 AU$) Annual GOS: $8.6 million for GBRMP; $1.1 million for Cairns (2009 AU$) Assumed no net loss from bleaching for recreational fishing.
(Deloitte Access Economics 2017) GBRMP Fisheries	Currency: 2015-16 AU$ Data for commercial fisheries & aquaculture: Queensland Department of Agriculture, Forestry & Fisheries (DAFF) (year not provided) Employment numbers are on Full- time equivalent basis (FTE) (2015-16)	Annual gross revenues for all commercial fishing and aquaculture in the GBRMP: $199 million (2015-16 AU$) • $95 million from line, net, pot and trawl fishing • $9 million from harvest fisheries • $95 million from aquaculture Annual value added from commercial fishing & aquaculture (2015-16 AU$): AU$139 million for the GBR regions; $140 million for Queensland Total; $162 million for Australia Total (of which $116 million is direct value added) Employment (2015-16): 680 FTE for GBR; 690 for Queensland Total; 814 for Australia Total (507 FTE directly for Australia Total)	Currency: 2012 Data: Recreational fishing was valued within "Recreation" expenditures. An estimated 3.4 million fishing trips took place in 2012 based on (Rolfe, Gregg, and Tucker 2011). Data for expenditure on recreational equipment: Australian Bureau of Statistics Household Expenditure Survey 2009–10 Data for recreational activities undertaken at GBR: "Valuing local recreation in the Great Barrier Reef, Australia," a survey conducted by John Rolfe et al. (2012)	Annual recreational expenditure (2015-16 AU$): $415 million • Equipment: $241 million • Fishing: $70 million • Boating: $26 million • Sailing: $15 million • Visiting an Island: $62 million Annual value added for Recreation (2015-16 AU$): $284 million for GBR Regions; $296 million for Queensland Total; $346 for Australia Total (of which $206 million is direct value added) Employment (2015-16): 2,889 FTE for GBR; 2,964 for Queensland Total; 3,281 for Australia Total (2,352 FTE directly for Australia Total)
(Teh, Teh, and Sumaila 2013) GBR *Reef* Fisheries (2005 US$)	Currency: 2005 US$ Data: Landed values attributable to 200 reef fish species and taxon groups from Sea Around Us database for 2005. Estimates based on assumed proportion factor of GBR to Australia is .87.	Annual gross landed "value" from GBR *reef* fisheries: US$407 million per year (2005 US$) Annual number of reef fishers: 25,810 (2005)		

chemistry of seawater flowing over a reef flat by adding the base sodium hydroxide (NaOH), resulting in increased net community calcification (Albright et al., 2016a). The authors point out that this approach would probably only be practical for small-scale

Table 2
Great Barrier Reef Coastal Protection: Estimated Economic Value.

Study	Currency year and data year for Coastal Protection Estimate	Estimated GBR Coastal Protection Values
(Cesar, Burke, and Pet-soede 2003 as cited in Oxford Economics 2009) GBRMP	Currency year: 2009 AU$ (adjusted in Oxford Economics (2009)) Data year: Cesar et al. (2003) value of US$629 million per year (currency year provided) for all of Australia's coral reef based on benefit transfer from Hawaii coral reef valuation that included 2001 property values	Annual coastal protection value: $438 million per year (2009 AU$)
s(Oxford Economics 2009) GBRMP (used interchangeably with the GBRWHA)	Currency year: 2009 AU$ Data year: Replacement cost ($2,300 per meter in 2009 AU$) based on a 2005 study of revetment wall in South Mission Beach, Australia	Annual coastal protection value: $5.3 billion per year for GBRMP (2009 AU$)

Table 3
Reef-related visitor expenditure from Spalding et al. (2017) Table A1 (Spalding et al., 2017). Data retrieved for years 2008–2012 where possible. Local currency data was converted to US$ values for 30 June of relevant year and these values were then converted to 2013 values using the Consumer Price Index (CPI) price deflator.

Country or Territory	Sum of reef- associated tourist arrivals (trip equivalents) per yr	Sum of reef- associated visitor expenditure (2013 US$ 1000/yr)	Reef visitor expenditure proportion of total tourism (per year)	Reef tourism as part of GDP (per year)	Mean value of reef (2013 US$ per km^2 per year)
Australia	1,877,513	$2176	2.41%	0.14%	$51,883

parts of reefs such as protected bays and lagoons. It is estimated that 3.5–7.7% of Australian GDP would be required to preserve the Great Barrier Reef through artificial alkalinization of reef areas (Feng et al., 2016; Deloitte Access Economics, 2013).

Assisted evolution techniques aim at enhancing resilience of corals through e.g. selective breeding of particularly resistant corals, epigenetic programming, genetic modification of the microbial communities associated with corals, or inoculation of corals with *Symbiodinum* species grown under high CO_2 and temperature to confer resistance. Combining reef restoration with *assisted evolution techniques* to outplant corals resilient to climate change and OA is an active area of research, however, these methods are in the 'proof-of-concept' stage and have not yet extended to field trials.

There are many uncertainties as to the efficiency and costs of these techniques (see Albright and Cooley, this special issue). Most of these techniques will serve only to restore or sustain a subset of ecosystem services at local to regional spatial scales, thus buying time to address carbon emissions as the root source of climate change and OA. It is clear that there is a need to assess the safety and cost-effectiveness of any new methods through the assessment of feasibility and efficacy of intervention options using strategic scientific trials and cost-benefit analyses. Albright et al. (2016b) suggests a theoretical framework for managing the GBR for OA in space and time, based on risk theory. Acting on reducing local stressors and spatial planning may be sufficient in areas and at times when the GBR is considered to be moderately affected by OA. When risks from OA increases, unconventional management strategies may be deemed appropriate. Given the vast area and different characteristics of the GBR, managers are likely to need to work across this framework at any given time. To be sure, any actions must be undertaken as part of a suite of global-scale interventions including atmospheric CO_2 reduction to preserve coral reef ecosystem function and benefits to humanity.

8. Recommendations for future action

To complement the long history of management of the GBR we propose a suite of actions that would help assess and increase the region's preparedness for OA. These actions address six key dimensions for preparing ecosystems and societies for the impacts of OA: (1) climate protection measures; (2) adaptive capacity of reef dependent sectors; (3) OA literacy; (4) area-based management for resilience; (5) research and development; and (6) policy coherence:

- Further enhancing measures to build resilience to climate change and OA, for example through implementing an effective climate policy that addresses OA, including targets for emissions level; renewable energies; and efficiency.
- Supporting the adaptive capacity of reef-dependent sectors, for example by developing an understanding of the vulnerability of these sectors and communities, identifying adaptation options, and developing sectoral strategies for responding to risks from climate change and OA (e.g. action plans, milestones, measurable outcome indicators).
- Enhancing OA literacy among the public and decision-makers, including accountability for climate dedicated government infrastructure (e.g. dedicated departments, technical assistance, education and outreach) and the incorporation of curriculum material on OA (e.g. within high school teaching schedules).

Table 4
Reef-related Tourism Attributable to the Great Barrier Reef: Estimated economic value.

Study	Currency year and data year for Tourism Estimate	Estimated Tourism Economic Contribution
(Spalding et al. 2017)	Currency: 2013 US$ Data: 2008-2012 Tourism expenditures determined as proportion of total visits and spending and based on spatial distribution (hotel distribution, geo-located photographs, and number of dive shops); arrival data largely derived from UNWTO	Annual reef-associated visitor expenditure: $2.2 billion (2013 US$) Annual reef-adjacent expenditures: $473 million (2013 US$) Annual on-reef expenditures: $1.7 billion (2013 US$)
(Deliotte 2013)	Currency: 2012 AU$ Data: Tourism expenditures based on number of visitor days and estimated average daily expenditure of domestic and international visitors in 2011-2012. Reef-specific tourism activity was based tourism operator logbooks. Assumed the expenditure ratio between catchment and the Reef for domestic visitors applied international visitors.	Annual reef-related tourism expenditures: $481 million (2012 AU$) Annual value added (economic contribution) from reef-related tourism: $389 million ($218 direct value added) (2012 AU$) Employment: 4,831 FTE (3,368 direct employment)
(Oxford Economics 2009) GBRMP (used interchangeably with the GBRWHA)	Currency: 2009 AU$ Data for Producer Surplus (PS): Expenditure and visitor nos. (unadjusted from 2002-03) from Bureau of Tourism Research (2003) and GOS/Expenditure ratio (.15) from Australia Bureau of Statistics (2008b) Data for Consumer Surplus (CS): Based on 579,000 international overnight visitors; 279,000 domestic overnight visitors; & 207,000 domestic day visitors (between 2002-03 – not adjusted for 2009 levels) using Cairns airport exit survey data from Nov 2006-June 2008. The study assumed 50% of overnight & 100% of day visitors were motivated by coral site visitation. We adjusted annual producer surplus figures based on adjusted present values of producer surplus provided in study. The PV of PS of $7.1 billion for GBR was adjusted to $3.6 billion (1.97:1 ratio) so the annual PS of $202 million was adjusted to $102 million; the PV of PS of $5.6 billion for TNQ was adjusted to $2.8 billion (2:1 ratio) so the annual PS of $160 million was adjusted to $80 million. Annual adjusted consumer surplus figures were provided in the study.	Annual expenditures for all coral site visitors (regardless of whether motivated by reef's existence): $1.3 billion for the GBR & $1.1 billion for Tropical North Queensland (2009 AU$) Annual GOS (Producer Surplus) for all coral site visitors (regardless of whether motivated by reef's existence): $202 million for the GBR and $160 million for TNQ (2009 AU$) Annual Adjusted GOS (Producer Surplus) (to reflect only those motivated by the reef's existence) for all coral site visitors: $102 million for the GBR and $80 million for TNQ (2009 AU$) Annual Adjusted Consumer Surplus: $474 million for GBR coral sites and $333 million for TNQ (2009 AU$)
(Deloitte Access Economics 2017)	Currency: 2017 AU$ Data for domestic tourist consumer surplus: based on 268 domestic survey responses that were representatively spread across states and territories (year not provided) Data for recreational consumer surplus: based on benefit transfer from (Rolfe and Gregg 2012) which collected survey data from six regional cities in GBR (data of surveys not provided)	Annual consumer surplus for GBR domestic tourism: AU$1.5 billion (2017 AU$) Annual consumer surplus for GBR recreation: AU$170 million (2017 AU$)
(Carr and Mendelsohn 2003) GBR	Currency: 2000 US$ (according to Oxford Economics (2009) but currency year not provided in original study) Data:; a sample of 607 people were interviewed between 1 Sept and 1 Dec 2000.	Annual consumer surplus for GBR tourism: US$710 million - US$1.6 billion per year (about $400 million accrued to domestic visitors) (2000 US$)

– Increasing compliance with area-based management, especially for locations found to be OA refuges, including through the establishment of management plans that explicitly support resilience to OA and programs in place to measure and report on the effectiveness of management.

– Additional investment in R&D relating to OA impacts and responses, including building capacity through training programs and international partnerships.
– Improving policy alignment and coherence across jurisdictions and sectors, including commitment to evidence-based decision-making that is consistent within and between governmental departments. It is important that policies aiming to deal with the issue of OA are not offset against other policies that might render a response to OA ineffective.

9. Conclusion

The recent recognition and integration of targeted actions to respond to climate change and OA in an integrative manner as outlined in the Reef 2050 Plan is encouraging. Given the long history of intense management and substantial investment into research and protection of the Great Barrier Reef, other countries and ecosystem managers look to the GBR for management best practices, lessons learned, and international leadership, and the specific inclusion of climate change actions in the management of the reef is a positive way forward. Considering the scale of recent destruction, much more needs to be done much faster, both globally and locally, to protect the GBR, its ecosystems, associated services, and its outstanding universal value as a World Heritage Site. The northern, most pristine, areas of the GBR were affected by the bleaching events in 2016–2017, highlighting the fact that global change leaves no area unaffected and local solutions can only protect the reef to a limited extent from climate change.

It is particularly important that any management decisions are based on the best available science, and that this science is designed to inform management through developing, testing, and refining potential measures while also filling knowledge gaps. Local solutions to mitigate OA effects on coral reefs face the challenge of scalability and can only buy time; therefore, they cannot be used as a reason for delaying action on CO_2 mitigation. That said, given the vast wealth of the GBR, protecting portions of the Reef and buying time should continue to be the focus of management efforts. Adapting reef management to the implications of OA will require an integrated approach that has the central goal of rapidly reducing global carbon emissions, while simultaneously supporting climate adaptation, and increasing investment in local and regional management actions that reduce other threats such as water quality and the crown-of-thorns starfish (see Tables 1–4).

Acknowledgments

OHG is grateful for the support of the Australian Research Council Centre for Excellence in Reef Studies as well as an ARC Laureate Fellowship.

This work was supported in part by the International Atomic Energy Agency Ocean Acidification International Coordination Centre (OA-ICC), Austria, supported by several Member States via the IAEA Peaceful Uses Initiative, Austria. The IAEA is grateful for the support provided to its Environment Laboratories by the Government of the Principality of Monaco.

This paper is an outcome from the 4th International Workshop "Bridging the Gap between Ocean Acidification Impacts and Economic Valuation — From Science to Solutions: Ocean acidification on ecosystem services, case studies on coral reefs" held in Monaco from 15–17 October 2017. The authors are particularly grateful to the workshop organizers, including the Government of Monaco, the Prince Albert II Foundation, the IAEA Ocean Acidification International Coordination Center (OA-ICC), the French Ministry for the Ecological and Solidary Transition, the Oceanographic Institute — Prince Albert I of Monaco Foundation, the Monegasque Water Company and the Monegasque Association on Ocean Acidification (AMAO) and the Centre Scientifique de Monaco (CSM).

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